SEMI-ANNUAL

REPORT

NASA GRANT NsG-711/44-07-004

HEAT TRANSFER ACROSS SURFACES IN CONTACT: PRACTICAL EFFECTS OF TRANSIENT TEMPERATURE AND PRESSURE ENVIRONMENTS

April 1, 1965, to October 1, 1965

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The objectives of this study have been and still are to study heat transfer across surfaces in contact under transient conditions. By transient conditions we include cases where the contact resistance stays the same and the thermal environment is changed, where the thermal environment remains constant but the contact resistance is changed, or combinations of these. While this research is basic in nature it is hoped that useful information for analysis of existing systems and for design and control of new systems will be forthcoming.

OBJECTIVES

We have approached this research both from theoretical and experimental viewpoints. In order to design the experimental equipment we made a theoretical study of a model which we planned to build. This theoretical study involves both analytical and numerical solutions of one-dimensional heat transfer across surfaces in contact where the source temperature was suddenly imposed upon the system which had been at a uniform initial temperature. The temperature-time position information which resulted was obtained for various combinations of materials, lengths, and contact resistances in order to estimate the time to approach a new steady state value. These theoretical correlations were presented by Blum and Moore* (1) (See also Appendix B).

CURRENT THEORETICAL STUDIES

In addition to the above, the effect of suddenly changing the contact resistance in a system which has been in steady state is now being correlated and studied. At present the theoretical studies involve (1) the development of an implicit method for studying the one-dimensional case,

FUTURE THEORETICAL STUDIES

*NOTE: Numbers refer to references.

(2) a numerical method for handling two-dimensional heat transfer in systems which have surfaces in contact, and (3) an analytical study involving the problem where convection from the surfaces are important. With regard to theoretical work it is our intention for this year and the next to (a) complete and summarize the one-dimensional studies, (b) to continue consideration of the two-dimensional problem with emphasis on a system in which many cylinders are placed on a plate, (c) to continue the studies involving rate of emptying and filling the interstices of a contact with fluids, and (d) start theoretical work on a new concept of changing surface contact area to affect control of heat flux.

CURRENT EXPERIMENTAL RESULTS

In all these cases mentioned above it is hoped that the theoretical studies will help with our plans for the experiments. The background information for these studies are described in the Appendix A.

The experimental portion of this work to date has consisted of designing and building a system to study the transient response of cylinders in contact when subjected to changes in the thermal environment, the ambient pressure, and the contact pressure. Experiments have been conducted on two sets of samples, a stainless steel-stainless steel set (type 304) and an aluminum-aluminum set (type 2024-T6). The experiments run so far for which data were recorded and analyzed are summarized in the following table.

Samples	Number of Tests		
	Phase 1	Phase 2	Phase 3
SS-SS	2	2	---
AL-AL	6	6	2*

*(See 2. below)

The basic purposes of the testing done to date was to check the ability of the system to provide data and to determine what changes might be required. There have been several things learned which have contributed to the improvement of techniques and procedures. Some of the more important contributions are discussed below.

1. Earlier test data indicated a significant contact resistance at the source and sink contacts which caused large changes in the actual end temperatures of the sample when the axial load was changed. Application of an extremely thin layer of silicone grease has been found to solve this problem.

2. Data and experience have shown that the bellows method of providing axial force is inadequate for two basic reasons: (1) changes of the bell jar pressure between atmospheric pressure and a vacuum cause changes in the axial load, and (2) it is impractical for providing sudden changes or programmed changes in the axial load.

This has led to the decision to change the loading system to a hydraulic cylinder in which pressure is controlled by a servo-valve utilizing a direct feedback of axial force from a load cell (or load washer). This system will allow a fixed axial force to be maintained independent of the bell jar pressure or thermal expansion. It also has the further advantage of allowing accurately controlled variations in axial load such as ramp or sinusoidal changes in load.

3. Data has shown that there is very little radial heat loss with no insulation at all, thus permitting the use of a very light insulation to insure one-dimensionality. This is advantageous since it will not severely affect the thermal capacity of the sample, which is critical for the transient experiments.

The data taken so far has provided some significant information.

1. The measured time to reach steady state for both the SS-SS and the AL-AL tests is of the order of twice the predicted time using the simple, analytical model. Here again, however, the data shows that some changes are required. The choice of defining steady state as the time when the temperature drop across the slowest reacting portion of the system is 99% of the

steady state temperature drop across that portion of the system is not a good one because small errors in data cause large errors in this calculation.

Thus it has been decided to use a more practical value of 67%. This will greatly improve the accuracy of correlating theoretical predictions and experimental results.

2. The shapes of the transient temperature profiles have been found to be very amenable to curve fits thus allowing the determination of the transient contact conductance. The results are very interesting in that they show that the conductance does vary considerably with both temperature and axial load when these variables are changed. Some typical plots of these phenomena are shown in Figure 1.

   These phenomena could account for the difference in the time to reach steady state as measured from the data and as predicted by the analytical model which assumed a constant contact conductance.

All of the above mentioned changes in procedure and hardware are either accomplished or in process now. It is felt that with these modifications the data obtained will be of sufficient accuracy to allow good correlation of results with isolation of the various macroscopic effects.

FUTURE EXPERIMENTS

Effect of Contact Pressure and Temperature on Rate of Contact Conductance Change

The work with cylinders will be continued with various materials and combinations of lengths and contact conductances. This is where most of the experimental effort is being directed. By the time this series of experiments has been completed it is hoped that we will be able to know how conditions at the contact change during transient conditions and what the response will be of various systems that we will include in this study.

Other experimental problems which may receive some of our attention are described below.

Is a Contact Conductance Standard Possible?

One of the large problems that suggests itself from our studies is the lack of a standard through which meaningful statements can be made in predicting both the steady state and transient behavior of systems with contacts. This difficulty would be expected in view of the large number of variables that affect heat transfer across surfaces in contact. For example, it has been pointed out by others and we have observed that the nature of the surfaces and how they are mated affect the contact conductance significantly. In order to achieve some element of standardization we would like to propose and test the following idea. Suppose by a sand blasting technique we can develop a random surface; that is, one whose profile and roughness would be the same in all directions. We could prepare a standard whose hardness would be greater than any of the other samples, and do a series of heat transfer experiments against the hardened standard. The objective of this study would be to predict from experiments against a standard for a common type surface how various samples would behave when in contact with each other.

<u>Two-dimensional Heat Flow</u>

We would also like to perform a few experiments under transient conditions where the heat transfer is two-dimensional. This will probably take the form of a cylinder being placed against a plate.

<u>Passive Control System</u>

A final type of experiment would involve the passive control concept mentioned in the previous section.

<u>Electric Resistance Measurements</u>

Simultaneously with heat transfer it would be desirable to measure the transient electrical characteristics of the system.

PERSONNEL

PRINCIPAL INVESTIGATOR: Dr. Harold A. Blum

GRADUATE STUDENTS: Clifford Moore, Lenox Carruth, and Roy Lawrence.

UNDERGRADUATE STUDENTS: Several undergraduate students have been working with us on this project. These are Robert Ashley, Thomas Ashley, J. R. White, Dennis Bryant, and David Wood.

OTHER ASSISTANCE: Mr. Jack Anderson and Professor Norman Varner have helped with machinery and equipment. Several people from the computing center have also been of great assistance.

RESUME OF PRINCIPAL INVESTIGATOR (Dr. Harold A. Blum)

EDUCATION

B.Ch.E.	Rensselaer Polytechnic Institute	1942
M.S. Physical Chemistry	Northwestern University	1948
PhD. Ch.E.	Northwestern University	1950

PROFESSIONAL EXPERIENCE

1942-43	Philadelphia Signal Corps Procurement District, Assistant Engineer, Signal Corps Equipment.
1947	Teaching Assistant, Northwestern University.
1951-55	Graduate Lecturer, Southern Methodist University.
1955-57	Associate Professor, Petroleum Engineering, Texas Technological College.
1955-	Consulting activity in heat transfer, petroleum production, and design.
1957-	Professor, Mechanical Engineering Department, Southern Methodist University.
1963-	Consultant, Office of Research Analyses-Headquarters Office of Aerospace Research, U.S.A.F. Hollomon AFB. (Summer, 1963).

HONOR SOCIETIES

Sigma Xi
Phi Lambda Upsilon (Chemical)
Pi Epsilon Tau (Petroleum)
Sigma Tau (Engineering)
Pi Tau Sigma (Mechanical)
Blue Key (University-Service)
Alpha Phi Omega (University-Scouting Service)

PROFESSIONAL SOCIETIES

American Society for Engineering Education
American Society of Mechanical Engineering
American Chemical Society
American Society of Heating, Refrigeration, and Air Conditioning Engineers

SOME PUBLICATIONS (Co-Author or Author)

"Transient Phenomena in Heat Transfer Across Surfaces in Contact," (Blum and Moore). Eighth Heat Transfer Conf., ASME-AICH.E., August 1965, 65-HT-59.

Reports to Fourth Thermal Conductivity Conference, San Francisco, "Measurement of Vapor Thermal Conductivities: Low Vapor Pressure Materials."

"Heat Transfer Across Surfaces in Contact: Transient Effects of Ambient Temperatures and Pressures," (Blum and Moore).

"Heat Transfer Across Surfaces in Contact: Effect of Ambient Pressure Changes," R. L. Aaron and H. A. Blum, Preprint I, A.I.Ch.E. Meeting, September, 1963.

"Thermodynamic Investigation of a Refrigerant Expansion Engine," ASHRAE Journal, August, 1961. (T. M. Olcott and Blum).

"Casing Design," The Petroleum Engineer, April, 1957.

"Electric Log Interpretation in Low Resistivity Sands," Journal of Petroleum Technology, August, 1955. (Martin and Blum).

"Microlaterlog Versus Microlog for Formation Factor Calculations," Geophysics, April, 1954. (Smith and Blum).

"Unit Operations for Mechanical Engineers," Journal of Engineering Education, April, 1953.

"Method for Determining Wettability of Reservoir Rocks," Journal of Petroleum Technology, January, 1952. (Slobod and Blum).

"Wettability in Surface Active Agent Waterflooding," Oil and Gas Journal, December, 1952. (Moore and Blum).

"Absorption of Carbon Dioxide from Air by Sodium and Potassium Hydroxides," Industrial and Engineering Chemistry, December, 1952. (Blum, Stutzman, and Dodd.)

CURRENT RESEARCH ACTIVITY

A. Areas

1. Separation of Gases in a Vortex Tube (NSF G-19882)
2. Thermal Contact Conductance Studies
3. Vapor Thermal Conductivity-Low Vapor Pressure Materials

B. Grants: (Principal Investigator)

1. National Science Foundation Vortex Flow Research, 1961-65.
2. National Science Foundation Undergraduate Research Participation, 1963.
3. National Aeronautics and Space Administration Contact Conductance Research, 1964-

GRADUATE THESES DIRECTED

"A Simplified General Approach for Investigating the Suitability of a Rocket Motor Propellant as a Regenerative Coolant," H. A. Person, 1958.

"A Generalized Thermochemical Calculation Procedure for High Speed Digital Computers," E. R. Berry, 1958.

"Post-Irradiation Effects in Polypropylene and Other Polymers," T. E. Peace, 1959.

"Design and Development of Calcium Compound Process Industries in Andhra State of Indian," Subba Rao, 1959.

"Irreversibility in a Control Volume," R. Varhaug, 1959.

"Thermodynamic Aspects of Vortex Tube Performance," D. Harden, 1960.

"An Analytical Investigation of the Laminar Free Convection Boundary Layer of the Inclined Plate," C. Blackwell, 1960.

"Separation of a Carbon Dioxide Air Mixture in a Vortex Tube," D. Cole, 1960.

"An Expansion Engine to be Used in Vapor Cycle Refrigeration Systems," T. Olcott, 1960.

"A Thermodynamic Investigation of the Length to Diameter Ratio Effects in a Vortex Tube," R. Fullerton, 1961.

"A Study of the Joule Thompson Effect," C. Smith, 1961.

"Emittance of Translucent Material," R. Cox, 1962.

"Solids Mixing in Liquid Fluidized Systems," C. Wood, 1962.

"A Study of Fuel Cell Construction from Low Cost Materials," W. Long, 1962.

"A Study of Performance of a Uniflow Vortex Tube with a Carbon Dioxide Air System," R. Croston, 1962.

"Factors Affecting Design of Fluidized Heat Exchangers," J. Pruner, 1963.

"Transient Conduction Across Surfaces in Contact," J. Walther, 1963.

"Effect of Ambient Pressure Changes in Heat Transfer Across Contacts," R. L. Aaron, 1963.

"An Experimental Study of Flow Regimes and Gas Separation in a Uniflow Vortex Tube," J. Wm. Browning, 1963.

"An Experimental Study of Flow Regimes and Gas Separation in a Split Flow Vortex Tube," W. A. Whitten, 1964.

UNIVERSITY ACTIVITIES (1964)

Faculty Senate, University Council, Admissions Committee, A.S.M.E. Advisor, APO (Service Organization) Advisor, SMU Representative to A.S.E.E., Religious Life Staff.

MISCELLANEOUS

1. Attendance at Institutes:

   Nuclear, 1959 — North Carolina State, Oak Ridge
   Transport Phenomena, 1961 — University of Wisconsin
   Transport Phenomena and Statistical Thermodynamics, 1963 — Stevens Institute of Technology

2. Outstanding Faculty Member (Engineering), 1962.

3. Submitted for publication, November, 1964, "Heat Transfer in a Decaying Vortex System," (Blum and Oliver).

4. Associate Investigator--"Feasibility of Regional Information Center," NSF (1960-61).

Resume of
C. J. Moore, Jr.

Received B.S.M.E. from SMU, 1959, Cooperative Program at Convair, Fort Worth as undergraduate; spent $2\frac{1}{2}$ years as Test Engineer, R & D solid rockets at Aerojet General Corporation, Sacramento; spent 9 months at Chance-Vought Corporation as a senior Propulsion Engineer. Received M.S.A.E. from SMU, 1964, presently working on Ph.D.

Resume of
Lenox Carruth, Jr.

Received B.S.M.E. from SMU, 1963, memberships in Pi Tau Sigma, A.S.M.E., ASTME, ARS, student trainee in Army Ballistic Missile Agency and Marshall Space Flight Center, NASA.

REFERENCES

1. Blum, Harold A., and Moore, Clifford J., Jr., "Heat Transfer Across Surfaces in Contact: Transient Effects of Ambient Temperatures and Pressures, Fourth Conference on Thermal Conductivity, San Francisco, California, October, 1964; Progress Report.

2. Aaron, R., and Blum, H., "Heat Transfer Across Surfaces in Contact: Effect of Ambient Pressure Changes", Preprint I, A.I.Ch.E., Puerto Rico, September, 1963.

APPENDIX A

Heat Transfer Across Surfaces in Contact: Theoretical Study

1. Continued Study of One-Dimensional Heat Flow Across Surfaces in Contact:

The theoretical studies to date, both analytical and numerical, have resulted in some correlation that enable us to predict the temperature-position-time, behavior of a large number of systems. Up to this point, we have been concerned with the time to approach steady state and the overshoot which has been described in the paper which follows this section. There are other correlations which might also be useful as well as expanding the program to consider cases where the thermal conductivity and diffusivity of the materials that we check can be functions of temperature and not constant as we have considered them.

Our preliminary studies with an explicit numerical method for handling a two-dimensional heat transfer problem involving contacts indicate that the machine time as contrasted to the one-dimensional case is greater by a factor of about sixty. It is possible that an implicit method for numerically solving this equation may allow us to save time while taking larger time and geometrical increments. In order to test this idea we are developing the implicit method for our one-dimensional program which has already been tested. As soon as this is developed we may be able to apply this to the two-dimensional cases.

2. Heat Transfer Across Surfaces in Contact: Two-Dimensional.

The possibility of a single sink removing heat from several sources simultaneously is the basis for this phase of our study. For example, one could consider a number of power transistors placed against a common plate.

The transistors could have different temperatures and there could also be a variety of heat fluxes. The questions which we think we can solve by numerical solutions are these: (1) How will a single cylinder in contact with a plate react to changes in contact resistance and thermal environment changes? (2) How will more than one cylinder placed in contact with a common plate react when subjected to both changes in the thermal environment and in the contact conductance? (3) How closely can various cylinders be placed on this common plate without significant thermal interference? We have already developed a numerical method for considering the case of one cylinder in contact with a plate. Our first runs have indicated that machine time could be prohibitive in cost. It is for this reason that we are planning to modify the method and possibly evaluate the implicit approach mentioned above.

3. A Theoretical Study of a Possible Control Application:

An idea for a passive control of heat flux using surfaces in contact could be evaluated in part theoretically. The concept involves placing two materials in contact. The contact area and pressure would vary depending on the temperature level of the two materials in contact. This could be achieved in several ways. For example, if two conductors, having slightly dished out sections in one or more places, were placed in rigid contact, as the temperature increased the two materials would be forced together which would increase the heat flux and thereby tend to decrease the temperature. If the materials were elastic within the range of the temperature changes when the temperature levels decreased the area of contact would decrease, likewise the heat flux. This could be studied analytically starting with a couple of simple models. The results will indicate under what conditions, if any, that this approach will be feasible. Figure 2 shows a possible arrangement.

4. The Rate of Emptying and Filling Interstices of a Contact:

Aaron and Blum*[2] did some initial work in which there was concern with the rate of emptying and filling contacts with fluids. If the interstitial gas conductance is a significant portion of the total conductance across a contact, then the speed of emptying or filling contacts could become important. It is the intention of theoretical work in this area to study the conditions under which this rate might significantly affect the transient response of systems in contact. The work by Aaron and Blum was limited to consideration of a parallel plate type model. It would be hoped that more realistic models might be studied.

Transient Phenomena in Heat Transfer Across Surfaces in Contact

HAROLD A. BLUM   CLIFFORD J. MOORE, JR.

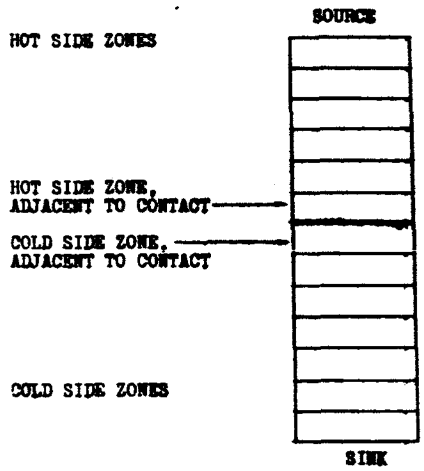

Fig. 1 Schematic of system with one-dimensional heat transfer across contact, which shows zones for which separate nodal equations were used

NOMENCLATURE

a = length of region 1
α = thermal diffusivity
b = length of region 2
$h = q''/\Delta T_c$ = unit contact conductance
k = thermal conductivity
L = total length of system = $a + b$
q'' = heat flux
T = temperature
t = time
x = distance from source

Subscripts

1 = region 1
2 = region 2
c = contact
f = final
i = initial value
L = x = L
0 = x = 0
(x) = position
t = time
n = summation index

INTRODUCTION

This study is concerned with two types of transient situations when heat is transferred across surfaces in contact. In the first situation the response of the system (with a constant thermal-contact conductance) to a changing temperature environment is calculated. In the second situation the effect of sudden changes in contact conductance on heat flux and temperature distribution is observed. The information obtained from this type of study could be of value for thermal-control purposes and for determination of the contact conductance.

In this investigation both the analytical approach and a numerical method were used to simulate a one-dimensional heat-transfer experiment. This method is applicable to two systems in contact where the relative and absolute lengths, material combinations, and contact conductance can be varied under all ranges of practical interest.

The system and boundary conditions for the two situations, for which the results are presented, are described as follows:

1 Starting with a uniform temperature, one end of the system is subjected to a different temperature (kept constant throughout the experiment) until steady state is approached. "Steady state" is defined as the condition where the temperature drop across the slowest reacting portion of the system is within 1 percent of its true steady-state value. Metal properties and contact conductance are constant.

2 Starting with steady-state temperature distribution, the contact conductance is suddenly changed to a new constant value until another steady-state condition is reached. Metal properties and end temperatures are constant.

Correlations are presented which are concerned with the first situation. These deal with (a) relation of the time to reach steady state (as defined in the foregoing) to the system geometry, metal properties, and contact conductance, and (b) the "overshoot" phenomena (transient conditions under which the temperature drop across the contact exceeds the steady-state value).

METHOD OF STUDY

Both the numerical and analytical methods, used to obtain the information for the data, required use of a digital computer. Chronologically the analytical method which was developed later than the finite-difference approach represents a check on the numerical method, a verification of the applicability of Tittle's quasi-orthogonal function method[1] for handling composite systems, and finally added a flexibility in this case which was thrifty of computer time. If it becomes desirable to vary the properties continuously, then the limitation of the analytical approach will necessitate the use of the numerical method.

Numerical Solution

A finite-difference approximation of Fourier's equation in one dimension was applied to the system consisting of two metals in contact.[2]

There were four zones requiring separate nodal equations for iteration in this explicit method. These zones are illustrated in Fig. 1.

For zones on the hot side (except that, adjacent to the contact) the nodal equation is

$$T_{1(x),t+1} = \frac{(T_{1(x-1),t} + T_{1,(x+1),t})}{M_1} + \left(\frac{M_1 - 2}{M_1}\right) T_{1(x),t} \qquad (1)$$

The equation for the zone of the hot side, adjacent to the contact is

$$T_{1(c),t+1} = \frac{2T_{(c-1),t}}{M_1} + \frac{2N_1 T_{2(c),t}}{M_1} + \left(1 - \frac{2}{M_1} - \frac{2N_1}{M_1}\right) T_{1(c),t} \qquad (2)$$

The equation for the zone on the cold side, adjacent to the contact is

$$T_{2(c),t+1} = \frac{2N_2}{M_2} T_{1(c),t} + \frac{2T_{2(2),t}}{M_2} + \left(1 - \frac{2}{M_2} - \frac{2N_2}{M_2}\right) T_{2(c),t} \qquad (3)$$

The equation for the remainder of the zones on the cold side is

$$T_{2(x),t+1} = \frac{T_{2(x-1),t} + T_{2(x+1),t}}{M_2} + \left(\frac{M_2 - 2}{M_2}\right) T_{2(x),t} \qquad (4)$$

where

$$M = \frac{\Delta x^2}{a\Delta t}$$

$$N = \frac{h_c \Delta x}{k}$$

In order to insure stable solutions it is necessary that the coefficients of all temperatures be positive on the right-hand side of equations (1) - (4). It was found that length increments of 0.1 in. and time increments of 0.01 sec achieved this stability and was sufficiently accurate so that no difference was observed between the analytical solution and this one.

Analytical Solution

The basis for the analytical solution of the space-time-temperature distribution is the separation of variables by product form in the governing partial differential equation. However, since the properties of the two regions are discontinuous at the interface, Fourier's equation must be written separately for the two regions.[3] Advantage is taken of the fact that the solution approaches the steady-state solution for large time by assuming the solution as a sum of steady-state and time-dependent parts. The solutions thus obtained by application of the interface and end boundary conditions are of the following form:

Region (1)

$$\frac{T_1(x,t) - T_i}{T_{1,0} - T_i} = 1 - C_1 x + \sum_n B_n \sin(\gamma_n x) e^{-\gamma_n^2 a_1 t}$$

Region (2)

$$\frac{T_2(x,t) - T_{2,L}}{T_{1,0} - T_{2,L}} = C_2(L-x) + \sum_n B_n [F_n \sin(\delta_n x) + G_n \cos(\delta_n x)] e^{-\delta_n^2 a_2 t} \qquad (5)$$

Where the eigenvalues γ_n and δ_n are determined by the equations

$$-\gamma_n = \frac{h}{k_2} \sqrt{\frac{a_2}{a_1}} \tan\left(\gamma_n b \sqrt{\frac{a_1}{a_2}}\right) + \frac{h}{k_1} \tan(\gamma_n a) \qquad (6)$$

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1 C. W. Tittle, "Boundary Value Problems in Composite Media: Quasi-Orthogonal Functions," Journal of Applied Physics, vol. 38, April, 1965, pp. 486-488.

2 G. M. Dusinberre, "Heat Transfer Calculations by Finite Differences," International Text Book Co., Scranton, Pa., chapter 6.

3 H. S. Carslaw and J. C. Jaeger, "Conduction of Heat In Solids," Oxford at the Clarendon Press, 1959.

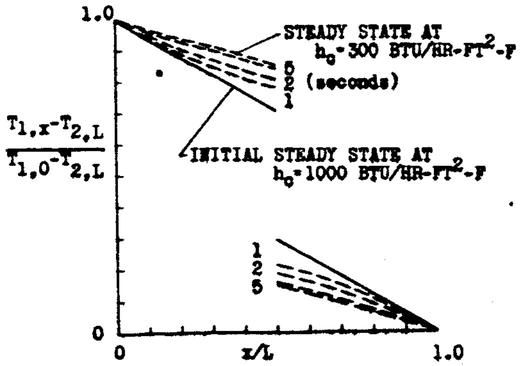


Fig. 2 Response of two 1-in. aluminum specimens in contact when contact conductance is suddenly changed

and

$$\delta_n = \gamma_n \sqrt{\frac{\alpha_1}{\alpha_2}} \tag{7}$$

The remaining series coefficients B_n are determined, as usual, by the application of the initial condition. However, ordinary Fourier analysis is inadequate here because the eigensets are not orthogonal over the full x-interval (0,L). These coefficients are determined by application of the theorem of quasi-orthogonality due to C. W. Tittle.[1] The final solutions thus obtained are as follows:

(a) For the initially uniform temperature distribution with a sudden increase in one end temperature the solution is:

Region (1)

$$\frac{T_1(x,t) - T_i}{T_{1,0} - T_i} = 1 - C_1 x - \sum_{n=1}^{\infty} \frac{2 \sin(\gamma_n x) e^{-\gamma_n^2 \alpha_1 t}}{D_n} \tag{8}$$

where

$$D_n = \gamma_n a - \frac{\sin}{2}(2\gamma_n a) + \frac{k_2}{k_1}\sqrt{\frac{\alpha_1}{\alpha_2}}\,[(F_n^2 + G_n^2)\delta_n b$$

$$+ (F_n^2 - G_n^2)\frac{\sin}{2}(2\delta_n a) + F_n G_n \cos(2\delta_n a)]$$

Region (2)

$$\frac{T_2(x,t) - T_{2,L}}{T_{1,0} - T_{2,L}} = C_2(L-x)$$

$$- \sum_{n=1}^{\infty} \frac{2[F_n \sin(\delta_n x) + G_n \cos(\delta_n x)]e^{-\delta_n^2 \alpha_2 t}}{D_n}$$

(b) For the initially steady-state temperature distribution with conductance of h_i with a sudden change in conductance to a new constant value, h_f, the solution is:

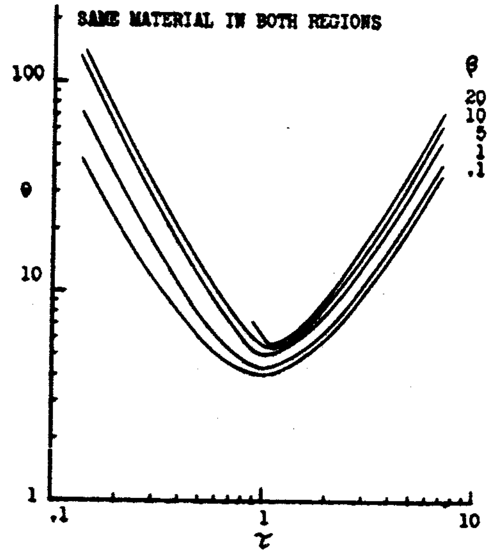


Fig. 3 Approach to steady state - same materials

Region (1)

$$\frac{T_1(x,t) - T_i}{T_{1,0} - T_i} = 1 - C_1 x$$

$$+ \sum_{n=1}^{\infty} \frac{2k_1 C_1 \left[\frac{h_i - h_f}{h_i h_f}\right] \cos(\gamma_n a) \sin(\gamma_n x) e^{-\gamma_n^2 \alpha_1 t}}{D_n} \tag{9}$$

Region (2)

$$\frac{T_2(x,t) - T_{2,L}}{T_{1,0} - T_{2,L}} = C_2(L-x)$$

$$+ \sum_{n=1}^{\infty} \frac{2k_1 C_1 \left[\frac{h_i - h_f}{h_i h_f}\right] \cos(\gamma_n a)[F_n \sin(\delta_n x) + G_n \cos(\delta_n x)]e^{-\delta_n^2 \alpha_2 t}}{D_n} \tag{10}$$

Where the following notation has been used:

$$F_n = \frac{\frac{k_1}{k_2}\sqrt{\frac{\alpha_2}{\alpha_1}} \cos(\gamma_n a)}{\cos(\delta_n a) + \sin(\delta_n a)\tan(\delta_n L)}$$

$$G_n = -F_n \tan(\delta_n L) \tag{11}$$

$$C_1 = \frac{1}{a + \frac{k_1}{h} + \frac{k_1}{k_2} b} \tag{12}$$

$$C_2 = \frac{1}{a \frac{k_2}{k_1} + \frac{k_2}{h} + b} \tag{13}$$

It should be noted that for case (b), the

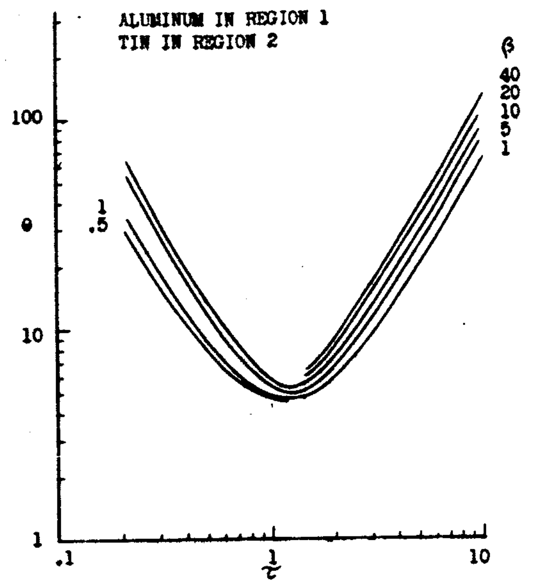


Fig. 4 Approach to steady state (aluminum-tin)

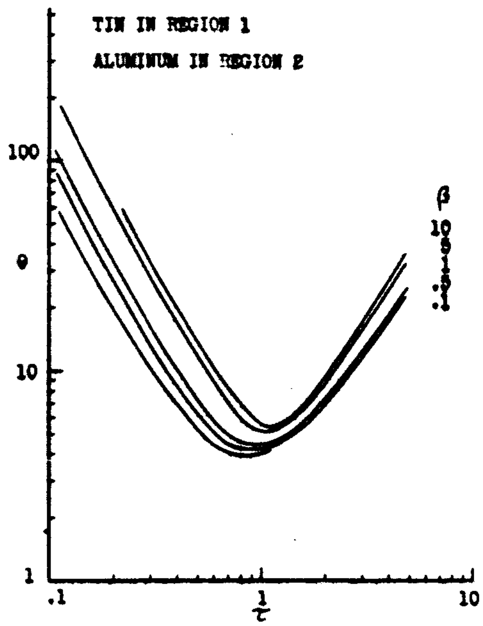


Fig. 5 Approach to steady state (tin-aluminum)

value of h in equations (6), (12) and (13) is the new value, h_f. For the cases studied, convergence of the series was obtained between 5 and 15 terms.

DISCUSSION OF RESULTS

The information obtained from the solutions previously discussed were temperature versus distance at various times. This was done for several materials, lengths, and contact conductances. Three of the possible ways to examine this large volume of information are described: (a) The complete history (temperature versus distance and time) for any specific case of interest would be useful in itself. (b) The time to reach steady state (defined arbitrarily as the time when the slowest reacting portion of the system was within 1 percent of the steady-state value) appears to be of practical importance. We concentrated most of our efforts on this phase of correlation. (c) The "overshoot" which represents the cases where the temperature drop across the contact exceeded the steady-state value during the transient period is another condition which may be of practical interest.

It should be pointed out that the agreement between the numerical and analytical solutions previously mentioned was excellent.

Fig. 2 shows the temperature versus distance at various times for the situation where a changing contact conductance occurs. Note that initially the contact conductance is higher as evidenced by the smaller temperature drop across the contact.

Figs. 3 - 7 represent correlations which are concerned with the time to reach steady state as defined in the foregoing. These correlations show the effect of geometry, material and contact conductance. All figures are plots of dimensionless time

$$\theta = \left(\frac{\alpha_1}{a^2} + \frac{\alpha_2}{b^2}\right) t$$

versus a "thermal time-constant ratio"

$$\tau = \frac{b}{a}\sqrt{\frac{\alpha_1}{\alpha_2}}$$

for various values of an "inverse Biot number" ($\beta = k_1/h\,a$). This is simply a method for representing the effect of the ratio of thermal "inertia" (τ) of the two regions on an effective time (θ) to reach steady state with the effect of the contact conductance included in β.

The minimum in θ that occurs shows that when $\tau > 1$, the dimensionless time is controlled by region 2 and that the control is with region 1 when $\tau < 1$. While β affects the position of the curve, the minimum is almost independent of β.

Fig. 3 is valid for all cases where the materials on both sides of a contact are the same. In developing data for this, materials ranged from stainless steel to magnesium, the ratio of region 1 length to region 2 varied from one to seven up to seven to one, contact conductances

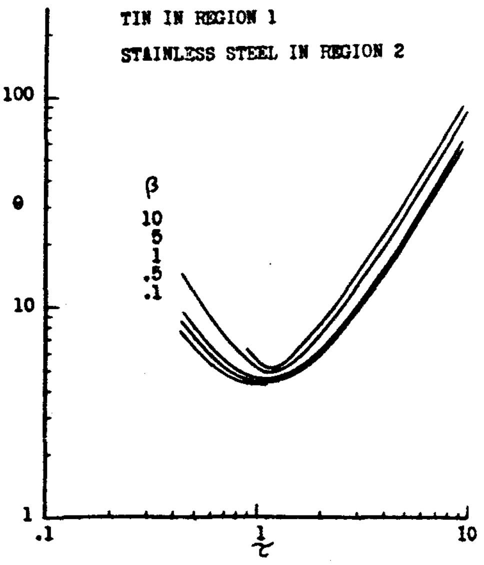


Fig. 6 Approach to steady state (tin-stainless steel)

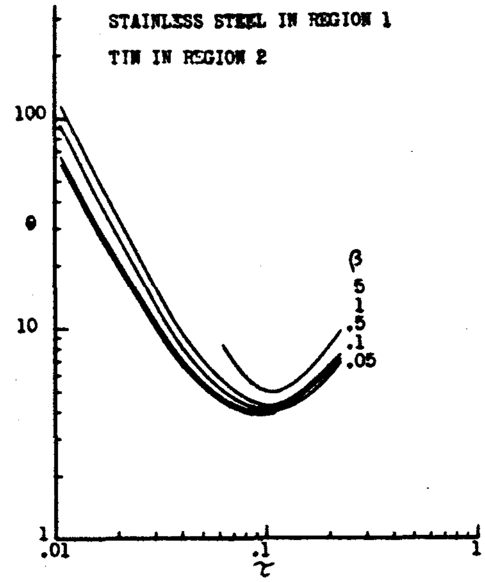


Fig. 7 Approach to steady state (stainless steel-tin)

were 25 - 4000 Btu/hr sq ft deg F (51.1×10^4 to 8200×10^4 watts/m^2 - deg K). The overall significance of this figure is that it is possible to estimate how long it would take a system to reach steady state when subjected to a sudden temperature change. It should be noted that this time is independent of the actual temperature difference imposed. From experimental data it would be possible to determine the contact conductance by estimating the time to reach steady state, for a system of known geometry and materials. These curves also show under what conditions the contact conductance would significantly affect the response of a system to temperature change and under what conditions the contact conductance would be relatively unimportant. The β-parameter shows the effect of contact conductance.

Consider the system consisting of 3-in-long aluminum in contact with a 1-in-long aluminum with a contact unit surface conductance of 1000 Btu/hr-sq ft-deg F. For $\tau = 0.333$ and $\beta = 0.47$, $\theta = 13$ (from Fig. 3), or the time to approach steady state is 73 sec. For this system where the conductance is 75, τ is still 0.333, β is 6.24, and θ (from Fig. 3) $= 26$, or the predicted time is 146 sec.

For the cases where the materials in region 1 and region 2 are not the same it becomes necessary to present the information on two separate charts for each material combination. For example, in Fig. 4 the aluminum-tin (that is, aluminum in region 1 and tin in region 2) is presented, whereas in Fig. 5, region 1 has the tin and region 2 has the aluminum. Figs. 6 and 7 show the correlations for the tin-stainless steel system.

While it would be desirable to present all this information in one or two figures it should not be surprising in view of the complexity of this composite system that this may not be possible.

The overshoot, as defined in the foregoing is a function of material, geometry, and contact conductance. It occurs for $\tau > 1$. In Fig. 8 this is shown as the ratio of the temperature difference across the contact to the steady-state temperature drop across the contact as a function of time for a 1-in. aluminum over a 1-in. stainless steel system ($\tau = 4.71$). It should be noted that the actual temperature drop across the contact is the product of the aforementioned ratio and the steady-state contact temperature drop. In the example of Fig. 8, the actual maximum temperature drop is 59.3 percent of the total temperature difference from source to sink for a contact conductance of 200. For a conductance of 1000 it is 24.0 percent, which is smaller (as would be expected) than the lower conductance case.

CONCLUSIONS

1 The numerical and analytical solutions for one-dimensional transient heat transfer across surfaces in contact are presented. These, when properly programmed, will provide temperature-position-time information for any combination of lengths, materials, and contact conductances.

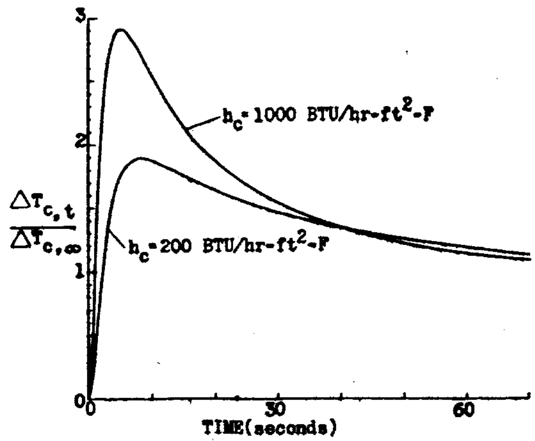


Fig. 8 The "overshoot": The effect of contact conductance on temperature drop across a contact for a 1-in. aluminum over a 1-in. stainless steel specimen when end of aluminum away from contact is suddenly exposed to a higher temperature than uniform initial temperature

2 The time to approach steady state is defined and some correlations are presented in terms of what may be governing dimensionless quantities. For the same material on both sides of the contact, one chart represents a large range of practical combinations of length, contact conductance, and metals. With different materials on either side of the contact, no general correlations were found so individual charts for each system, with a large range of length and contact conductance combinations are presented for a few cases.

3 The contact overshoot is another interesting phenomenon dependent on material, lengths, and contact conductance. The condition for the overshoot is a value of $\tau > 1$. No general correlations are presented for this phenomenon.

4 The value of this study will depend on the degree of experimental verification, since such assumptions as constant contact conductance during transients are only approximations. An experimental program is currently being undertaken.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial and other support of this investigation by the National Aeronautics and Space Administration under Grant NSG 711. They are also indebted to C. W. Tittle for his help with the application of his new method to our studies.

APPENDIX C

Experimental Program

Basically the experimental program consists of measuring the temperature distribution as a function of time in two metallic cylinders in contact with each other as shown in Figure 3. This transient distribution results from an upset in the system's one-dimensional heat transfer. At present three quantities are being used for these upsets: (1) source temperature; (2) axial force; and (3) environment pressure. Three types of upsets are currently being studied which consist of holding two of these quantities constant and varying the third rapidly from one fixed value to another.

From this data, analyses are being made which attempt to correlate such parameters as time required to reach steady state and transient contact conductance in terms of the thermal, geometric, and mechanical properties of the cylinders. For details the program is best described in the following four divisions.

A. Sample preparation

The first step is to construct the samples of the appropriate material. This is done by first cutting the bar stock to rough length and turning to the proper diameter ($1.000 \pm .001$ inches) in a lathe. Next the "outside" end of the sample is finished to a final roughness of 6-10 μin (RMS), and the thermocouple slots are cut in the outer surface to a width of 0.02 inches and a depth of 0.02. The nominal slot locations are at 0.1, .3, .5, .7, .9 of the sample length. Finally, the "contact" end of the sample is machined in a shaper so that the final desired length is obtained and the contact surface has the transverse lay to the required roughness.

While the sample is still in the shaper bed the indexing marks which reference the lay direction are put on.

After the machining the macro- and micro-hardness of the sample are determined and the assigned sample number is etched on the outer surface. Next the surface measurements are made on a Surfindicator. Then all this information along with all actual dimensions (including the slots' axial locations) are recorded in a log book. This log book is also used to record the sample history which includes everything that is subsequently done to the sample.

Sample preparation is concluded by installing the thermocouples into the slots and then applying the silicone rubber to provide strain relief for the thermocouple lead wires.

B. Thermocouple Calibration

Since the thermocouple readings are recorded on an oscillograph there is an electric current in the thermocouple circuits and therefore they must be calibrated against known temperatures. To eliminate additional sources of temperature error the thermocouple-wire-oscillograph system is calibrated as a unit just as it is used in taking data.

This is accomplished by placing the calibration bath adjacent to the test fixture and placing the samples (with thermocouples already in place) in the aluminum shavings, as shown in Figure 4. The sample is surrounded by the aluminum in the can, which is surrounded on all but one end by the oil bath, and insulated on the other end. The oil bath temperature is adjusted in large steps by the circulation of steam or cold water through the coils shown. When the approximate desired temperature is reached the controller takes over and controls the temperature to within $\pm$ .01°C. The actual temperature is recorded from readings of a set of calibrated ASTM standard thermometers, readable to 0.1°F. The bath temperature is adjusted to the desired value and controlled at that temperature for one hour. Then the oscillograph is turned on to record the deflection of the thermocouple traces for that temperature. This process is repeated for all desired calibration temperatures. It has been found to be advantageous to always take readings ascending and descending in temperature, since this procedure eliminates small errors in temperature which might be caused by thermal lag.

A computer program is used for the final step in the calibration procedure. The data from the oscillograph are punched on to cards and used by the program which fits the best second order curve through the data for each thermocouple separately, using standard least-squares techniques. Earlier, higher order curves were tried but they did not improve the accuracy. A typical set of calibration data and the least squares fit are shown in Figure 5. The regression coefficients are then used in the data analysis routine to calculate temperature from deflection of the oscillograph traces.

C. Data Acquisition

After calibration the samples are removed from the calibration fixture and cleaned with a soft brush to remove aluminum filings. The ends are then cleaned with acetone first and finally with absolute ethyl alcohol. The source and sink ends are then coated with a very thin layer of D.C. silicone grease to reduce the contact resistance at these locations.

The samples are then placed in the test fixture and aligned to the desired orientation of the lay on the contact surfaces. Then the tests are run according to the type of test desired. The three basic tests now being used are as follows:

Phase 1. This test can be run in the atmosphere or in vacuum. It is started by starting the sink coolant flow and allowing the entire sample to reach a uniform temperature. Using a room temperature sink has made this condition more easily obtainable. Once the uniform temperature is reached the oscillograph is turned on and then the steam valve to the source is opened. The source temperature rise is very rapid thus approximating a step increase. A typical oscillograph record of this type of experiment is shown in Figure 6.

Phase 2. These experiments can also be run at atmospheric pressure or in a vacuum. The experiment begins with a steady state heat flux through the samples. Then the axial loading is increased or decreased while holding the ambient pressure and the source and sink temperatures constant. The experiment continues until the new steady state is reached.

Phase 3. These experiments begin with a steady state heat flux through the sample with the system in a vacuum (lower than 10^{-4}mmHg). The ambient pressure is then returned to atmospheric pressure as rapidly as possible while holding the axial force and source and sink temperatures constant. Contact conductance is thus increased by the addition of the gas to the interstices and the transients in temperature distribution are observed.

D. Data Analysis

After an experiment is completed the data analysis begins with reading the trace deflections from the oscillograph record. Readings are taken at discrete times by measuring the deflection from the reference displacement by means of a ruler scaled to .01 inches. Time intervals at which readings are made depend on the transients themselves, i.e., where the changes are rapid, closer spacing of time intervals is used and where they are occurring slowly larger spacings suffice. These readings are recorded in a data log book and are referenced to the sample and experiment numbers. The oscillograph records (which are also appropriately identified) are stored. Next this recorded data is punched on to cards and read into the computer with the data analysis computer program.

At present the computer program performs the following operations:

1. Reads in the required data for the specific sample, such as thermal conductivities, diffusivities, sample lengths and exact thermocouple locations.
2. Reads in calibration data.
3. Calculates physical quantities from deflection data using the calibration results.
4. Prints out temperature distribution versus time (in tabular form).
5. Performs transient analysis. This consists of making least squares curve fits through the temperature profiles for each instant of time then projecting these to the contact boundary to compute the contact temperature differential. Next the heat flux is calculated from the local slope of the temperature profiles at the contact. Then from these two, contact conductance is calculated.

6. Prints out (in tablular form) the transient analysis.

7. Performs steady state analysis which consists of fitting the best least squares straight line through the steady state temperature profile and computing the correlation parameters described in Appendix B.

8. Prints out steady state analysis.

The computer program is quite flexible and any further analysis of the data which might prove to be desirable can be easily added. At present, additions to the program are being written which will allow for machine plotting of any of the desired data.

APPENDIX D

Equipment

For the purposes of illustration the experimental equipment currently in use is shown schematically in Figure 3 and in the photograph of Figure 7. Descriptions of the key components are given below.

During the experiments the sample is held between the source and sink blocks. These blocks are constructed of OFHC copper and are hollow with inlet and outlet ports. The sink block temperature is held constant by flowing room temperature water from a large reservoir. Steam from the building heating system is used to maintain the source temperature constant; the temperature is adjustable by means of controlling the pressure using a throttling valve.

All temperatures are measured with copper-constantan thermocouples using a reference temperature of $32^{o}F$, which is maintained in an insulated ice bath. The recording instrument for all data is a Honeywell Model 1508, twenty-four channel oscillograph, with paper speed adjustment from 0.1 to 80 inches/second.

Variation and control of the axial load is accomplished by means of a metal bellows using compressed air. The pressure in the bellows is regulated by means of an APCO model pressure regulator controlled manually.

The bellows and source and sink blocks are mounted in the stainless steel frame as shown in Figure 7, which itself rests on the base plate of the vacuum system. All electrical wires and fluid lines pass through feed-through connections in the base plate. The vacuum system is a Consolidated Vacuum Corporation Model system utilizing a roughing pump and an oil diffusion pump.

APPENDIX E

Figures

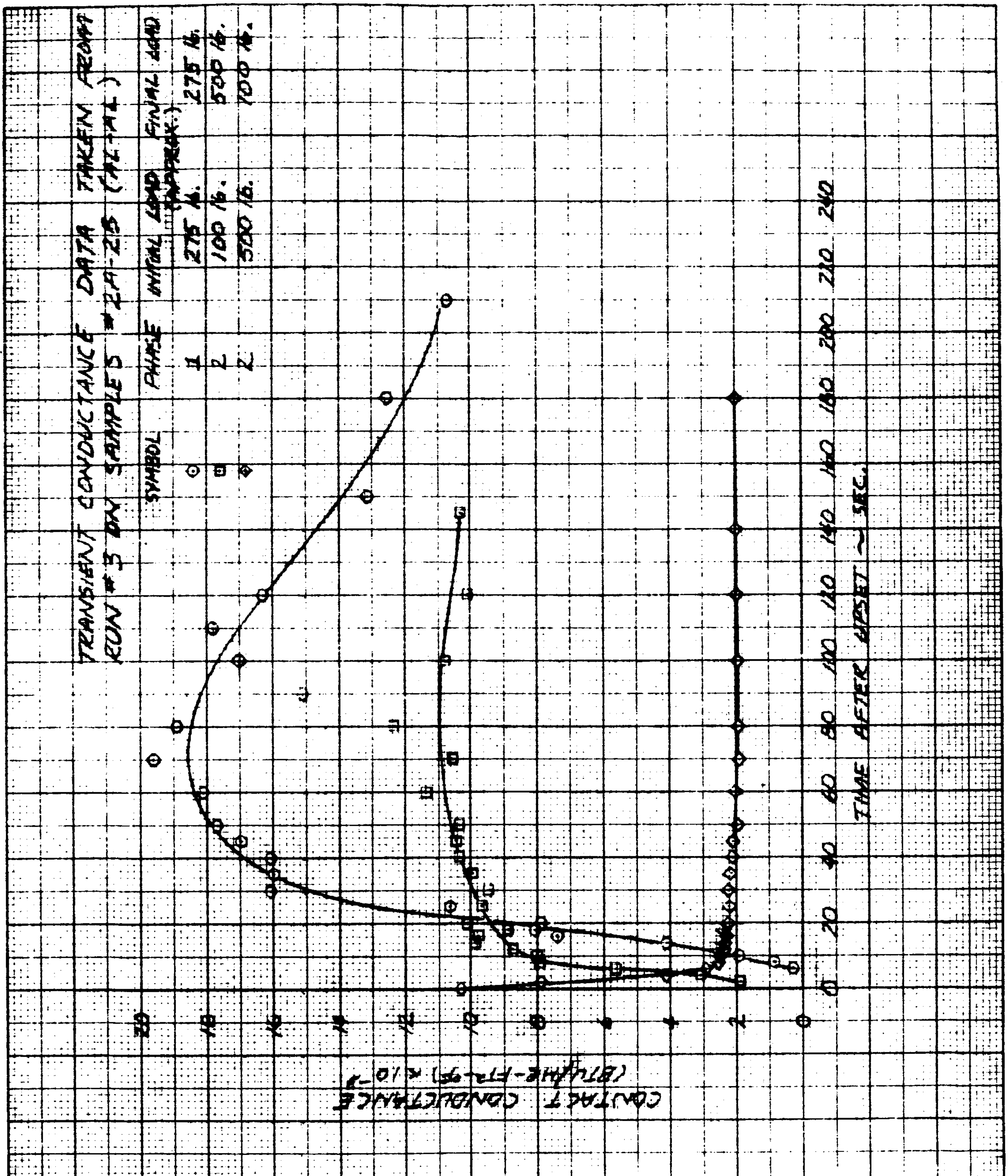

TRANSIENT CONDUCTANCE DATA TAKEN FROM
RUN #3 ON SAMPLES #2A-2B (AL-AL)
SYMBOL
PHASE
INITIAL LOAD
FINAL LOAD (APPROX.)
1
275 lb.
275 lb.
2
100 lb.
500 lb.
2
500 lb.
700 lb.
0
20
40
60
80
100
120
140
160
180
200
220
240
TIME AFTER UPSET ~ SEC.
0
2
4
6
8
10
12
14
16
18
20
CONTACT CONDUCTANCE
(BTU/HR-FT²-°F) × 10⁻³

FIGURE 1

RIGIDLY PLACED CONDUCTORS IN CONTACT

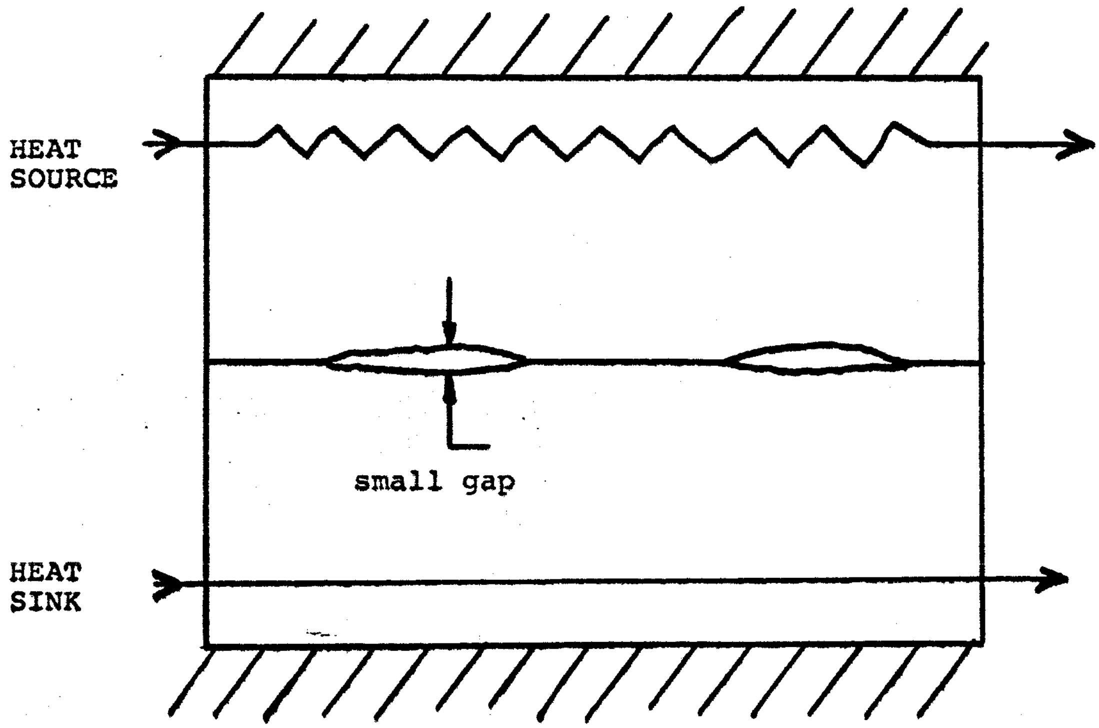


FIGURE 2 - PASSIVE CONTROL DEVICE

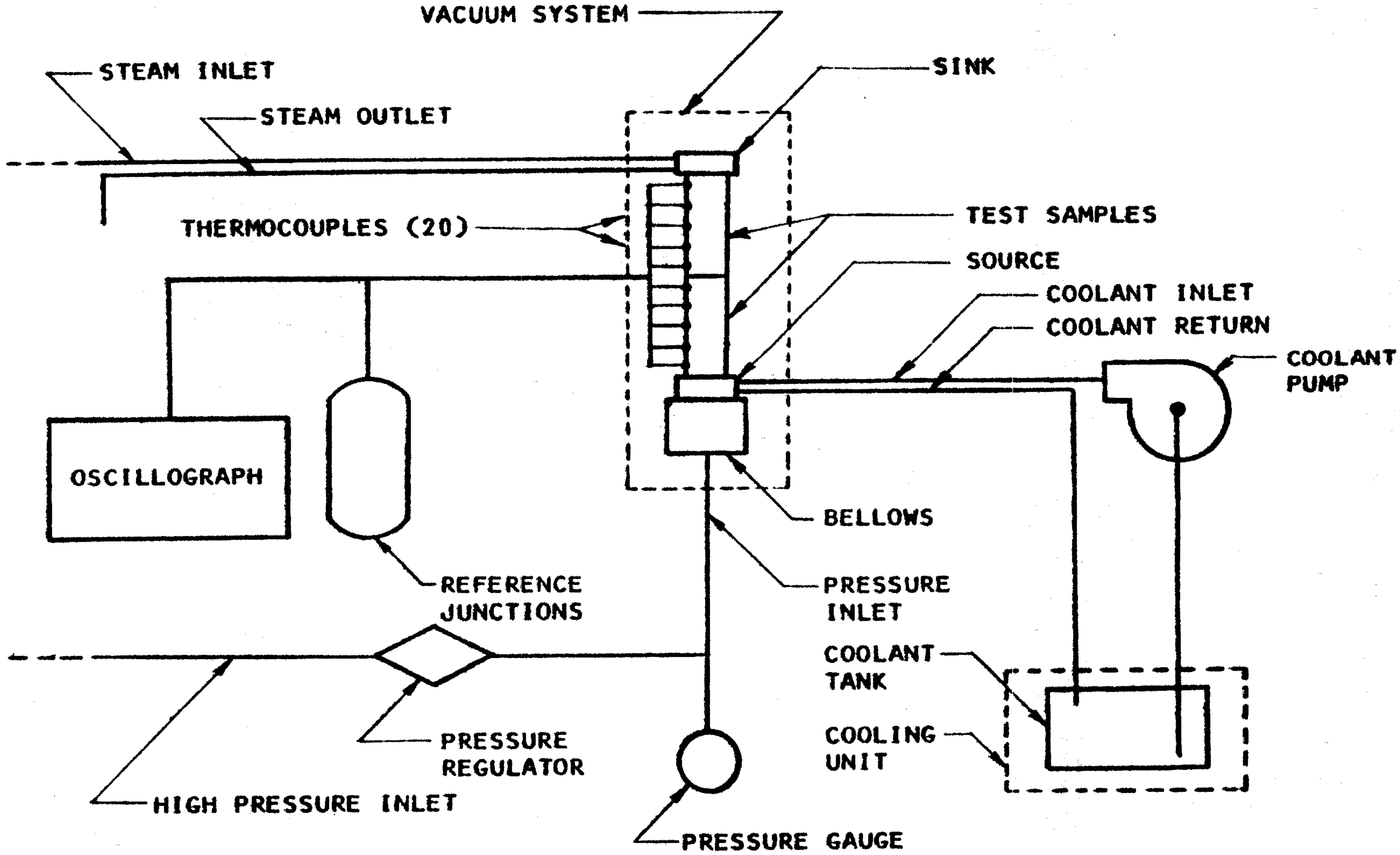

VACUUM SYSTEM
STEAM INLET
STEAM OUTLET
SINK
THERMOCOUPLES (20)
TEST SAMPLES
SOURCE
COOLANT INLET
COOLANT RETURN
COOLANT PUMP
OSCILLOGRAPH
BELLOWS
REFERENCE JUNCTIONS
PRESSURE INLET
COOLANT TANK
COOLING UNIT
PRESSURE REGULATOR
HIGH PRESSURE INLET
PRESSURE GAUGE

FIGURE 3

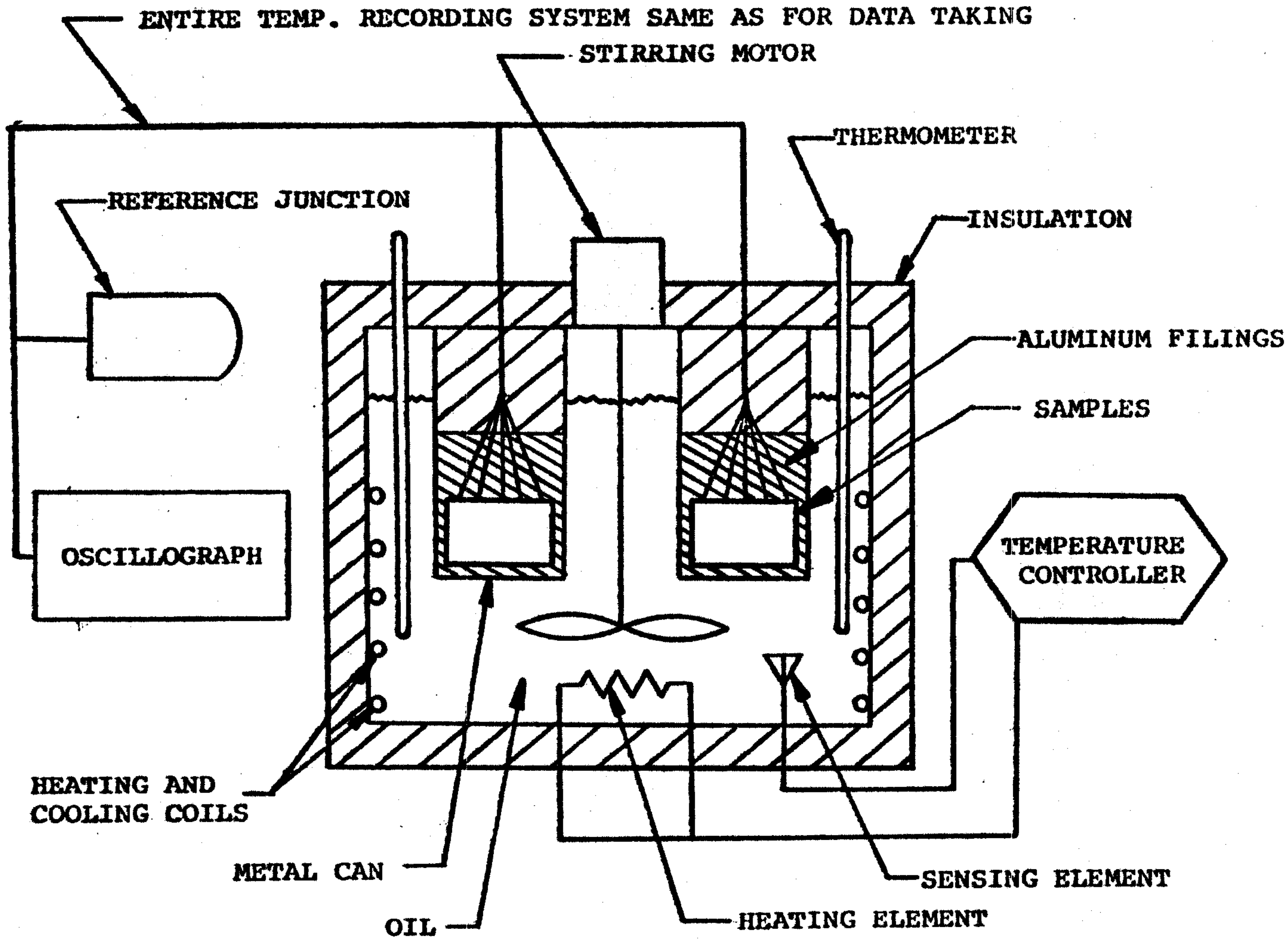
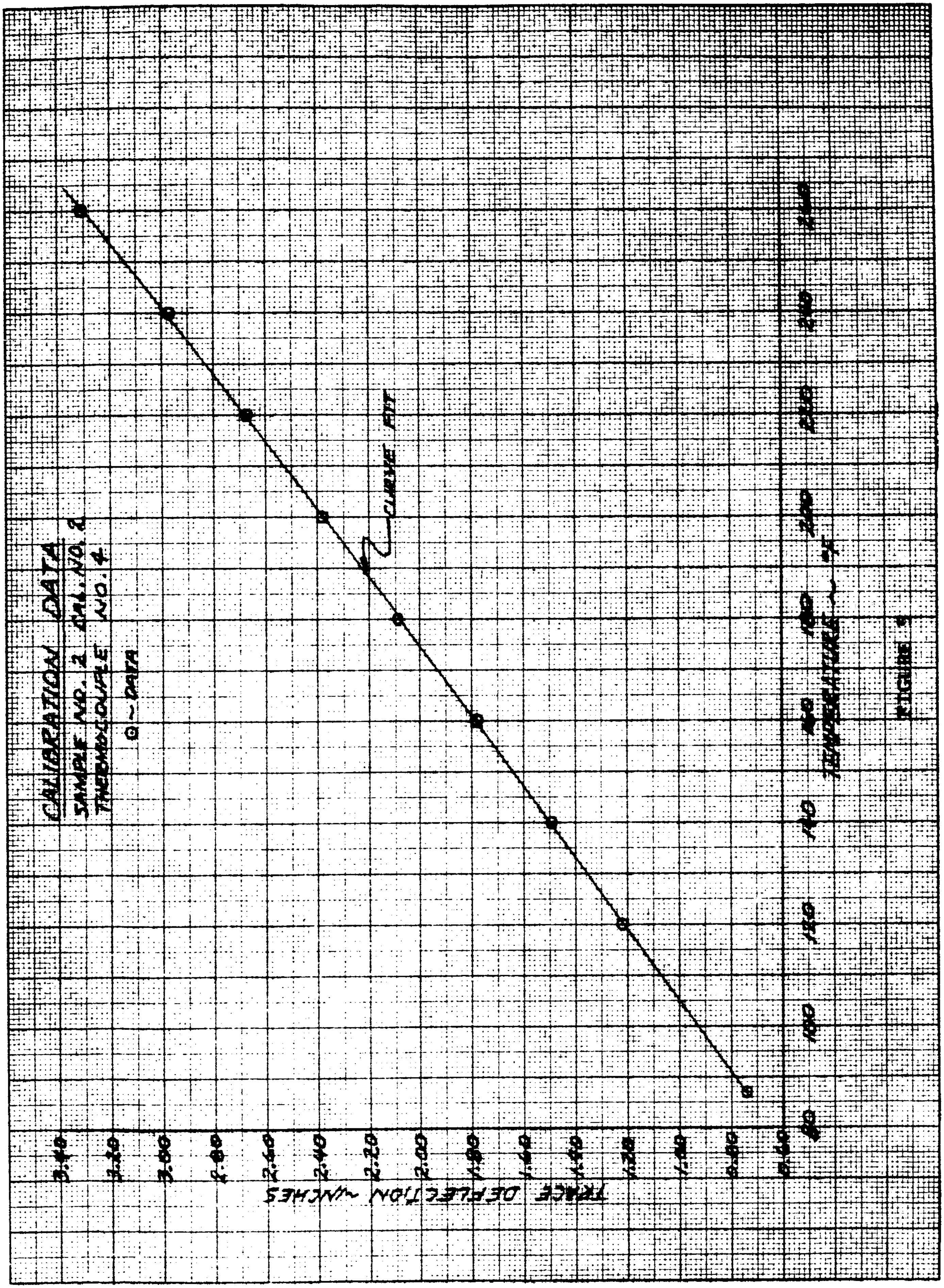


FIGURE 4-THERMOCOUPLE CALIBRATION SYSTEM


CALIBRATION DATA
SAMPLE NO. 2 DML NO. 2
THERMOCOUPLE NO. 4
⊙ ~ DATA
CURVE FIT
TRACE DEFLECTION ~ INCHES
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
80
100
120
140
160
180
200
220
240
260
TEMPERATURE ~ °F
FIGURE

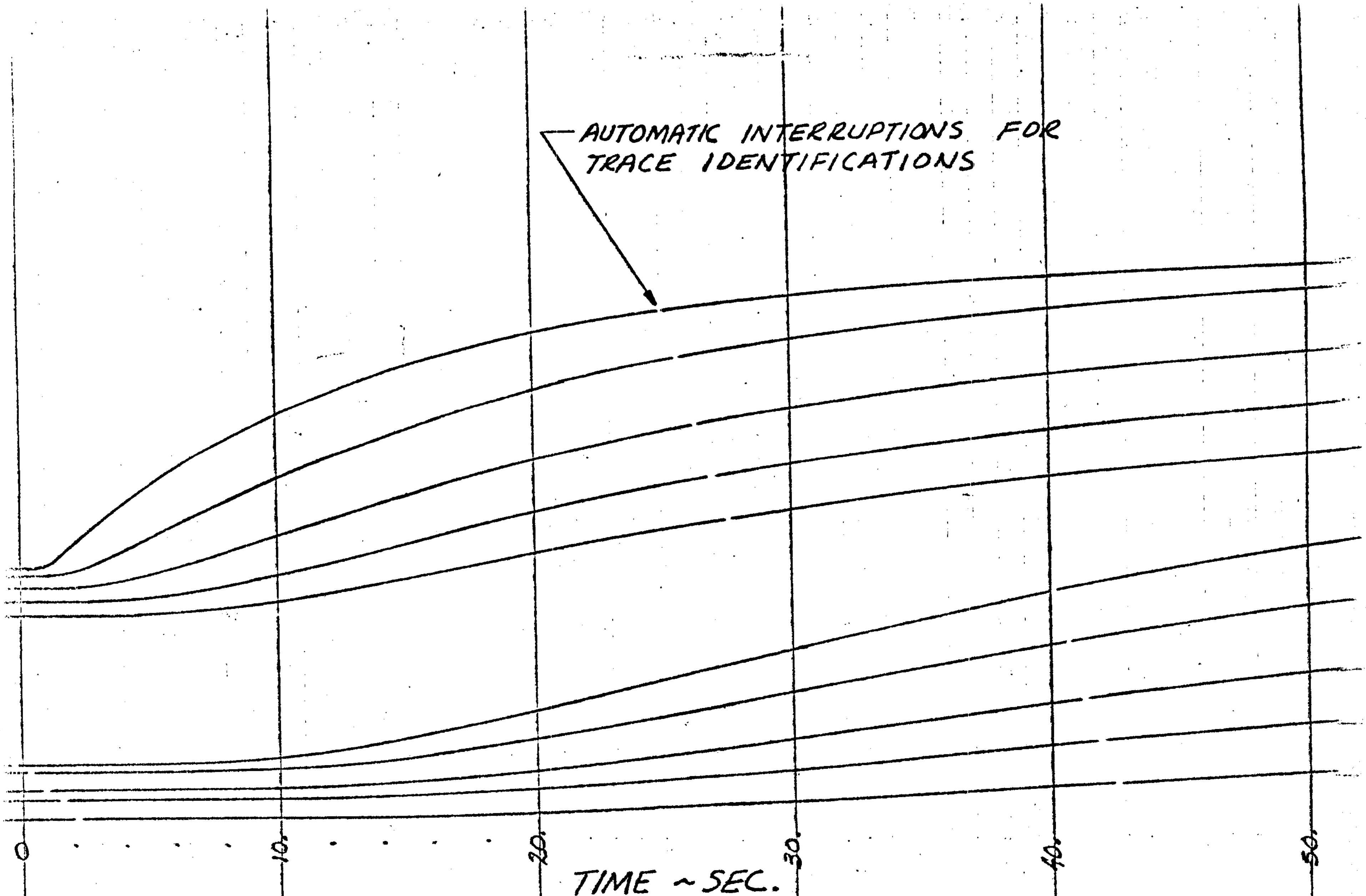


FIGURE 6. Typical oscillograph record in experiment where source temperature is suddenly increased (Each thermocouple has separate zero and sensitivity for better delineation)

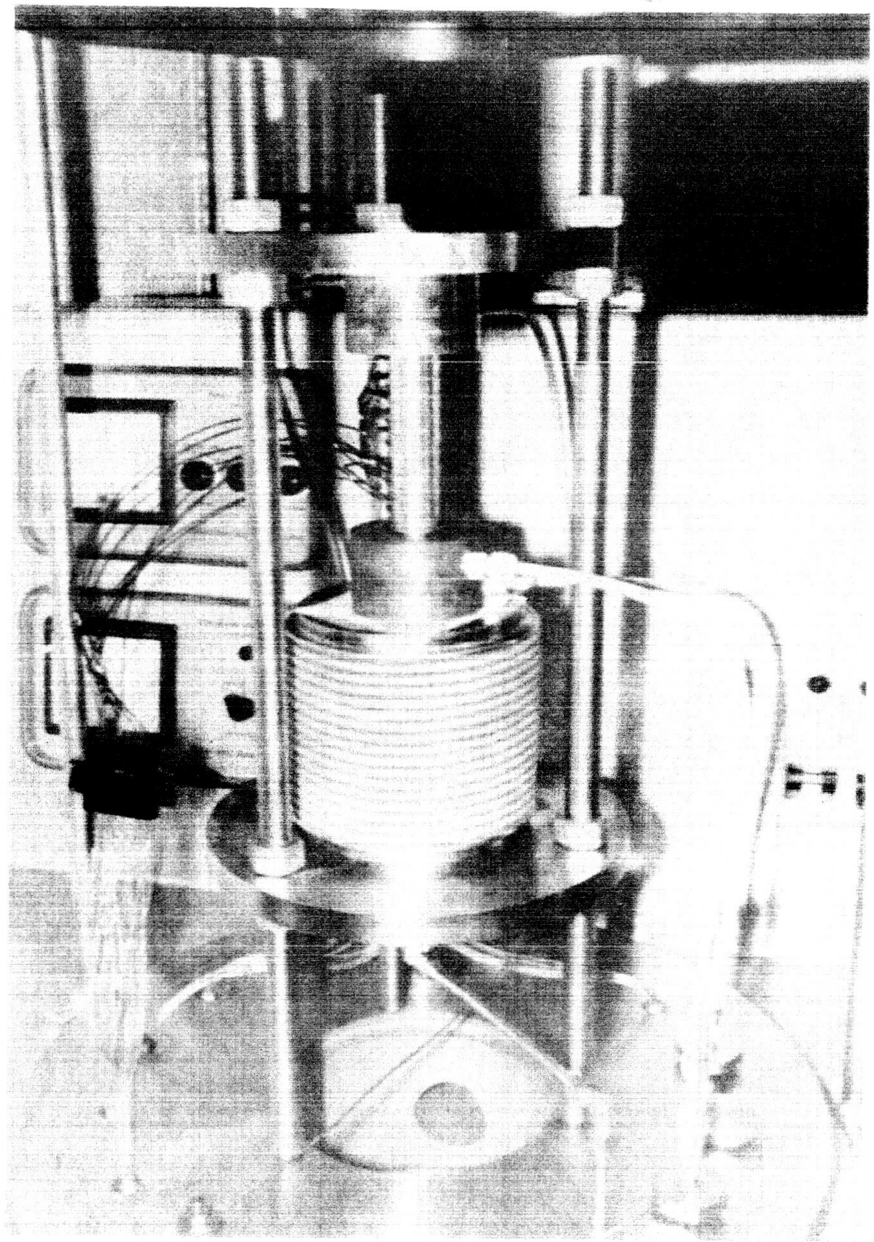


FIGURE 7

Test Section